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A CUSTOM MADE PHANTOM FOR DOSIMETRIC AUDIT AND QUALITY ASSURANCE OF THREE-DIMENSIONAL CONFORMAL RADIOTHERAPY

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ABSTRACT

The ultimate check of the actual dose delivered to a patient in radiotherapy can be achieved by using dosimetric measurements. The aims of this study were to develop and evaluate a custom handmade head and neck phantom for evaluation of Three-Dimensional Conformal Radiation Therapy (3D-CRT) dose planning and delivery. A phantom of head and neck region of a medium built male patient with nasopharyngeal cancer was constructed from Perspex material. Primary and secondary Planning Target Volume (PTV) and twelve Organs at Risk (OAR) were delineated using Treatment Planning System (TPS) guided by computed tomography printout transverse images. One hundred and seven (107) holes distributed among the organs were loaded with Rod-shaped Thermoluminescent dosimeters (LiF:Mg,Ti TLDs) after common and individual calibration. Head and neck phantom was imaged, planned and irradiated conformally (3D-CRT) by linear accelerator (LINAC Siemens Artiste). The planned predicted doses by TPS at PTV and OAR regions were obtained and compared with the TLD measured doses using the phantom. Repeated TLD measurements were reproducible with a percent standard deviation of < 3.5%. Moreover, the average of dose discrepancies between TLDs reading and TPS predicted doses were found to be < 5.3%. The phantom's preliminary results have proved to be a valuable tool for 3D-CRT treatment dose verification.

Keywords: head and neck phantom, thermoluminescent, 3D-CRT, verification

INTRODUCTION

The primary objective of radiotherapy is to maximize the therapeutic benefit of radiation treatments which mainly depends on delivering an accurate prescribed dose to the target volume with high spatial of the neighbouring healthy tissues. Assurance of accuracy of delivered dose may not be achieved by computer Treatment Planning System (TPS), as there are many possibilities of dosimetric errors

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between planned and delivered treatments from the first step of the simulation process to the execution of treatment. Previous literature reported significant inconsistencies between calculated doses by TPS and measured doses through in-vivo dosimetry especially in the critical structures (Chung et al., 2005).

Recently, Three-Dimensional Conformal Radiotherapy (3D-CRT) has been shown to improve dose distribution, with increased dose to the target volume and reduced dose to the surrounding normal tissues (Brizel et al., 1999; Lohr et al., 2000; Pommier et al., 2000; Rasch et al., 2002; Roa et al., 1994; Tsuji et al., 1986), but this depends mainly on the planner's expertise and requires effort in manipulation to improve dose distribution. Besides that, the sophistication and complexity of clinical treatment planning and TPS by 3D-CRT have led to the need for continuous quality assurance (QA) tests that can be applied to clinical treatment planning.

The most reliable way to check the accuracy of patient treatment and to assess the delivered dose to critical organs can only be achieved by dosimetric measurement. Consequently, using a sort of phantom with radiation measuring devices with the patient in place is highly recommended as a prerequisite for safe and efficient application of treatment plan. American Association of Physics in Medicine, Radiation Therapy Committee (AAPM-RTC) stated that phantoms made up of a material approximating soft tissue should be used in order to assess the patient contour accurately and verify the 3D-CRT techniques at both the commissioning and clinical stages. By exposing the phantom to a patient's set of beam, the actual measured radiation dose can be compared to the calculated dose for the phantom. Ideally, these phantoms should be anatomically realistic, have radiologic properties that are identical to those of the tissues concerned, and allow for a variety of measuring devices to be used to verify dose and it distribution in a number of key positions throughout the target and normal-tissue volumes (Report 44, ICRU, 1989). Other approaches have also been used to evaluate any treatment plan and delivery system combination (Ezzell et al., 2003; Galvin et al., 2004; Gillis et al., 2005; Kinhikar et al., 2007; Van Esch et al., 2002).

Webster et al., (2008) designed a semi-anatomic phantom of head and neck region using Perspex material, intended mainly for verification of IMRT treatments in the head-and neck region. Thimble ionization chamber (0.125cm^3: PTW, Freiburg, Germany) and a pinpoint chamber (0.015cm^3: PTW) were used for dose measurements. An agreement between the measured doses and calculated doses by TPS of nine clinical head-and-necks IMRT was found.

Molineu and his colleagues (2005) designed a head and neck phantom with plastic shell filled with water for dosimetric validation of IMRT. TLDs and radiochromic films were used to measure the absolute dose and the dose distribution in two PTVs and OAR areas by constructed the insert as a block of polystyrene housing solid water targets and an acrylic organ at risk. The authors suggested that the OAR was located at one area, but actually we have more than twelve (12) OARS at head and neck regions.

The availability of Perspex material and the similarity of its density to that of tissue and bone in the human head and neck region are considered when choosing Perspex for fabricating the current phantom. Previous study checked the validity of this density assumption by comparing the average density of the phantom, including oral cavity and oesophageal heterogeneities, to the average density of 7 head-and-neck patients. The mean patient density was found to be 1.073 g/cm3 (range: 1.018 – 1.236 g/cm3) as compared to 1.076 ± 0.003 g/cm3 for the phantom (Webster, 2008).

The introduction of thermoluminescent dosimetry (TLD) in radiotherapy has a long history and its use for dose measurements has been well documented in the literature (Cameron et al., 1968; Kron, 1999;

Mayles et al., 2000; Rudén, 1976; Van Dam and Marinello, 1994). The physical and the intrinsic characteristics as well as the system stability, reproducibility and calibration of TLDs batch were investigated by Lee et al. (2010). Their results suggested TLDs as a method to ensure the quality of the radiotherapy treatment. Furthermore, TLDs are often more suited to a point dose measurement in high gradient region because of their small size relative to ion chambers and this also allows multiple points to be measured simultaneously. However, usage of TLDs is labour intensive (Attix, 1986).

The present paper details the considerations involved in the design of an anthropomorphic head and neck Perspex phantom intended for 3D-CRT dosimetric verification.

MATERIALS AND METHODS

Phantom design and development

The anatomically realistic phantom of head, neck and shoulder regions that approximate the contours of a standard sized patient is shown in Fig 1.

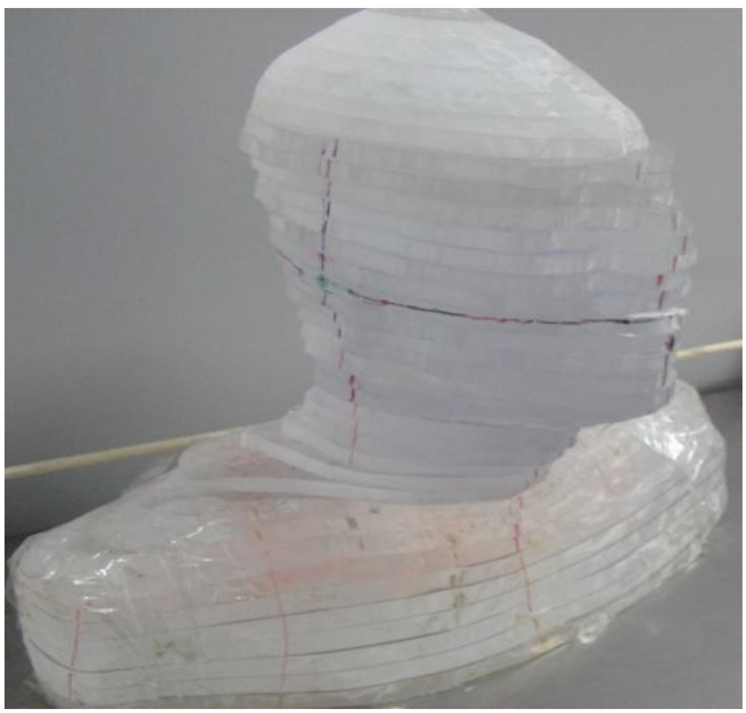

Fig. 2: Anthropomorphic Perspex head and neck phantom for dosimetric verification of treatment delivery

In designing the phantom, attention was paid to the adequate representation of dose distribution and the standardization of the phantom size and contouring (Fig. 2). Computed Tomography (CT) images for a series of nasopharyngeal patients using SIEMENS CT Scanner (SOMATOM Sensation Open, Germany) were obtained and transferred to TPS. With the collaboration of a group of physicists and a medical radiotherapist, the dimensions of the head and neck regions were obtained from TPS computer and the average was considered.

The primary and secondary Planning Target Volume (PTV) and Organ at Risk (OAR) regions were delineated by TPS, and the print out of transverse sections were obtained. By matching and contouring the images of the printed CT scan slices on Perspex boards, thirty-nine (39) slabs of Perspex were cut that when assembled they represented the model of a patient's head and neck region (Figure 2). Two perpendicular isocenter lines on the printed CT images were transferred at each Perspex slab as guidance for assembling the phantom.

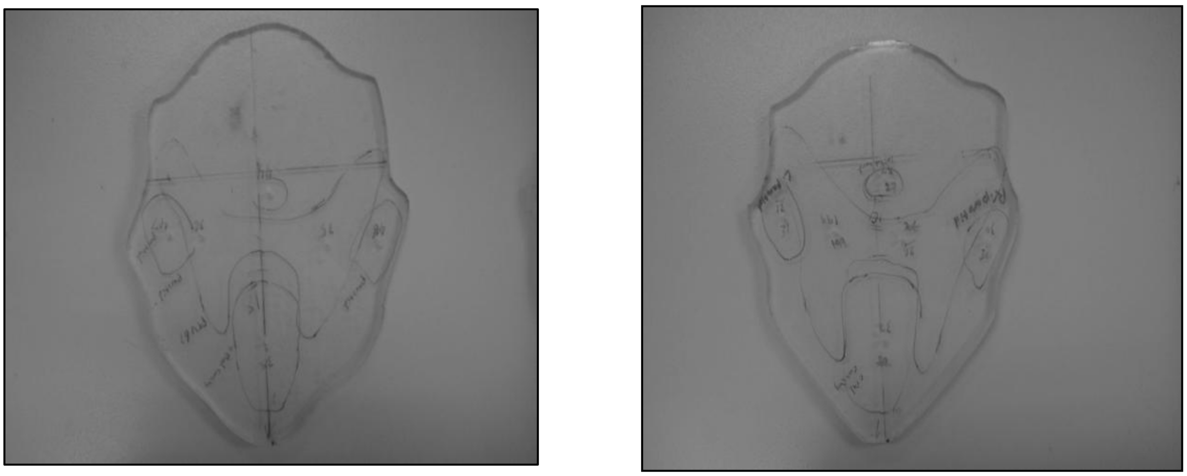

Fig. 2: Perspex slabs with delineated Organs at Risk (OAR) and Planning Target Volume (PTV) boundaries

Both sides of PTV and twelve (12) OAR were selected including; eyes (bilateral), parotid glands (bilateral), optic nerve (bilateral), temporo-mandibular joint (bilateral), brain stem, optic chiasm, larynx, and spinal cord. One hundred and seven (107) holes with dimensions of 1.5 mm (diameter) and 8 mm (depth) were drilled into various locations within OAR and PTV regions in each slab for placement of TLDs. All holes were drilled at least 1 cm apart, to avoid any influence on TLDs dose because of its higher density (2.64 g/cm^3) than Perspex material (Santvoort and Heijmen, 1996). A CT scan was performed to the fabricated phantom to ensure that the positions of TLDs were within the delineated organs (Fig 3). 3D-CRT treatment plan for nasopharyngeal cancer patient was imported and recalculation was done onto the CT images of the phantom.

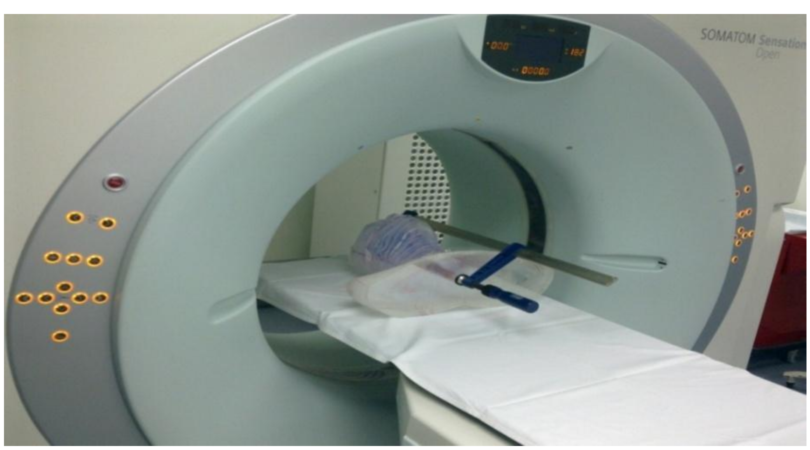

Fig. 3: Anatomical Perspex head and neck phantom during CT scan

TLDs annealing and calibration

Rod-shaped LiF:Mg,Ti TLDs (Bicron NE, USA) with dimensions of 1.0 mm diameter and 6.0 mm long were used in this study. All TLD-100 were annealed using Nabertherm oven (Nabertherm, Germany) by a thermal cycle: 1 h at 400 °C , followed by cooling for 2 hs, 24 hs at 80 °C in order to reduce fading when integrating intensity measurements (Horowitz, 1984; McKeever et al., 1995). The TLDs were selected after a careful initialization procedure (Furetta and Weng, 1998).

For TLDs calibration, a solid water phantom (Gammex RMI, Bad Munstereifel, Germany) and a calibrated ionization chamber (FC65-G, Wellhofer, Germany) were used (Attix, 1986). As it was difficult to make holes on solid water phantom to place TLDs, a number of Perspex slabs with dimensions (30 cm x 30 cm) and 4 mm thickness, were fabricated. Holes were drilled horizontally on each Perspex slab with dimension of 1.5 mm width x 8 mm length x 1.5 mm depth. Perspex slabs loaded with TLDs were inserted in-between the solid water phantom at d_{max}. A dose of 100 cGy was delivered from 6 MV photon beams linear accelerator (LINAC Siemens Artiste) at a Source-to-Surface Distance (SSD) of 100 cm with a (10 x 10 cm^2) field size. All TLDs were readout by TLD reader (Harshaw model 3500, USA) with a reading profile of: preheat temperature of 50 ºC for 0 s, acquire temperature rate 12 ºC/s, acquire maximum temperature of 300 ºC for 33 ⅓ s, and annealing temperature of 300 ºC for 0 s. Five subsequent calibration cycles for FC65-G ionization chamber were carried out to establish individual calibration factors. As the accuracy of TLD measurements depend on the reproducibility of the results as measured by the standard deviation of each individual calibration factor (Furetta and Weng, 1998; McKeever et al., 1995; Radaideh and Alzoubi, 2010; Yazici, 2004), five subsequent calibration cycles were carried out. TLDs with sensitivity < 5% were selected.

Percentage depth dose curve

PDD curve study was performed by exposing TLDs in Perspex and ion chamber in solid water phantom at different depths (ranging from 0 to 20 cm) and 10 cm thickness as full backscatter at reference setting. The correction factor ($K_{correction}$) was obtained as a ratio of M_w and M_p, where M_w is the average of 5 ion chamber readings at 1.5 cm in a water phantom and M_p is the average of 10 TLD readings at the same depth in Perspex phantom. All readings of ion chamber were corrected for water temperature and atmospheric pressure.

Phantom planning and reproducibility test

According to the reproducibility of calibration's results, out of 240 TLDs only 107 were chosen for the current study. The patient's thermoplastic mask, that was mainly used to reduce the errors originating from mobilization, was used to determine the three CT reference points on the phantom for irradiation. The phantom loaded with TLDs was shot by three identical 2 Gy fractions planned conformally by 3D-CRT with two lateral fields and a matching lower anterior neck field (Fig 4). After each shot, TLDs were read out, annealed and then reinserted into phantom slabs.

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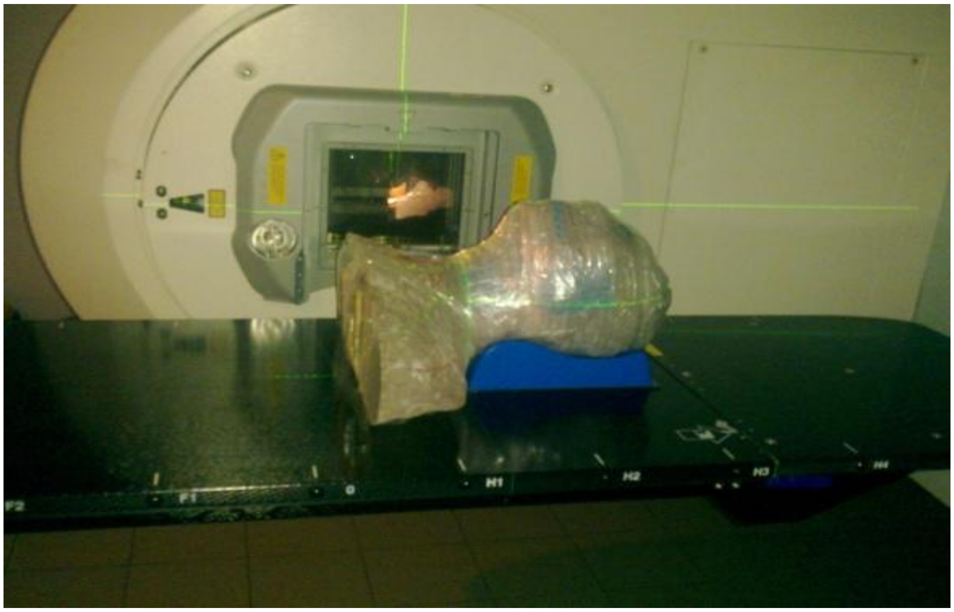

Fig. 4: Anatomical Perspex head and neck phantom during 3D-CRT treatment

Predicted doses at similar locations were obtained from TPS computer (Oncentra Maherplan V3.3) which uses pencil beam algorithm for dose calculations. All measured doses were compared to predict ones point-to-point. All data entry and analyses were conducted by Excel and SPSS software version 17.0 (statistical package of social sciences) programs.

RESULTS AND DISCUSSION

All TLDs were calibrated and the results displayed a linear response (R^2=0.998) with respect to the measured doses at d_{max} from 50 to 400 cGy. The main reproducibility of the TLDs was within 3% and the sensitivity 10% at one standard deviation.

PDD curves were graphed and the mean difference between both the measured doses values of TLDs and the ionization chamber was 2.9 % with a standard deviation of 4.8% with the largest differences at the build-up region (Figure 5). Discrepancies for all depth between d_{max} to 20 cm remained within 2.1% and a standard deviation of 2.6%. In previous study, Perspex correction factors were found to be 1.068 using TLDs and 1.063 using Monte Carlo simulation In agreement with this study, the correction factor is 1.064 (Lee et al., 2008). This correction replaces all corrections for sensitivity, phantom material, field size, and fading.

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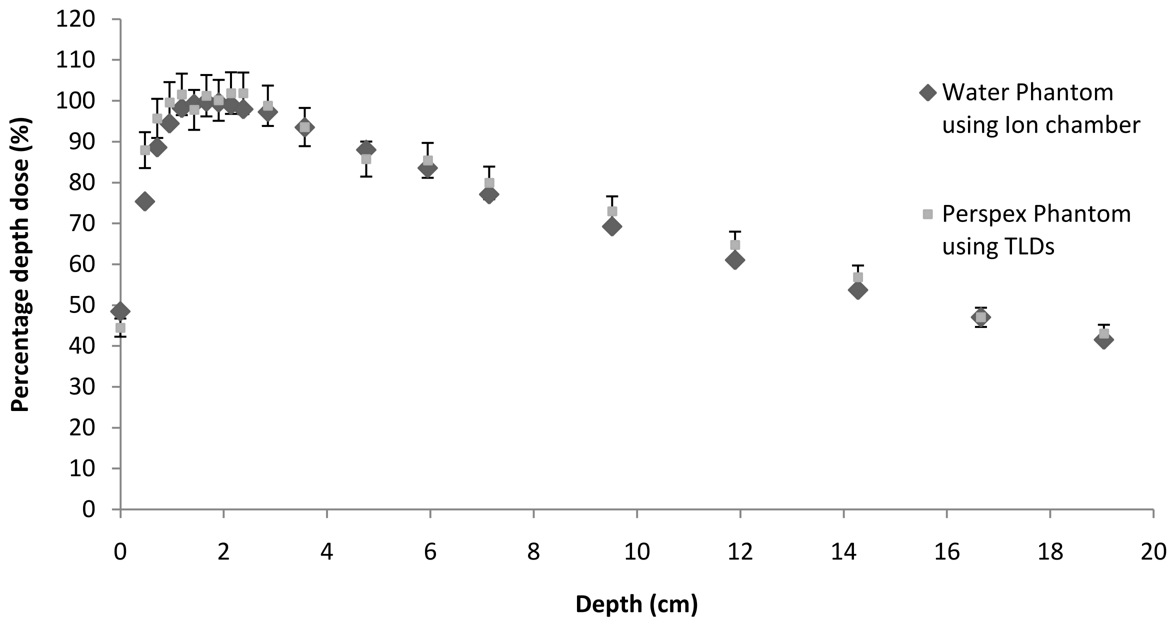


Fig. 5: Central axis depth dose distribution for 6 MV photon beam at field size (10 x 10 cm^2), SSD=100, using ion chamber in solid water phantom and TLDs in Perspex phantom

To test the validity of this phantom in term of reproducibility, the results of three identical TLDs irradiation showed a percent standard deviation of < 3.5%. Furthermore, the average of dose discrepancies between the average of TLDs reading and TPS predicted doses were found to be < 5.3% (Fig 6).

When the average doses of all TLDs located at each OAR and PTV region was compared to corresponding predicted doses by TPS, a good correlation was found, with the largest standard deviation of 5.3% at OAR, and 4.2% at the PTVs regions (Fig 7). This deviation between predicted and measured doses has met the accuracy criteria of 7% for dose in a low measurement gradient region and/or 4 mm distance to agreement in a high gradient (Ibbott et al., 2006; Molineu et al., 2005). A reason for such discrepancies in the dose delivery is the air gaps developed from the size difference between holes size and TLDs that was made to avoid TLD’s scratching or breaking when assembling the model.

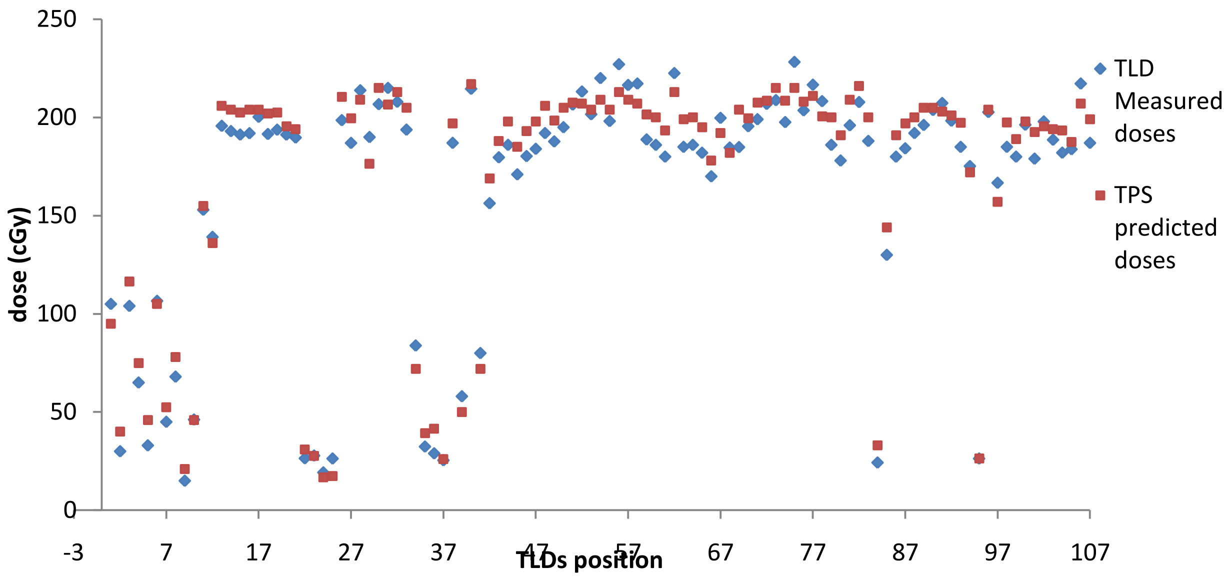
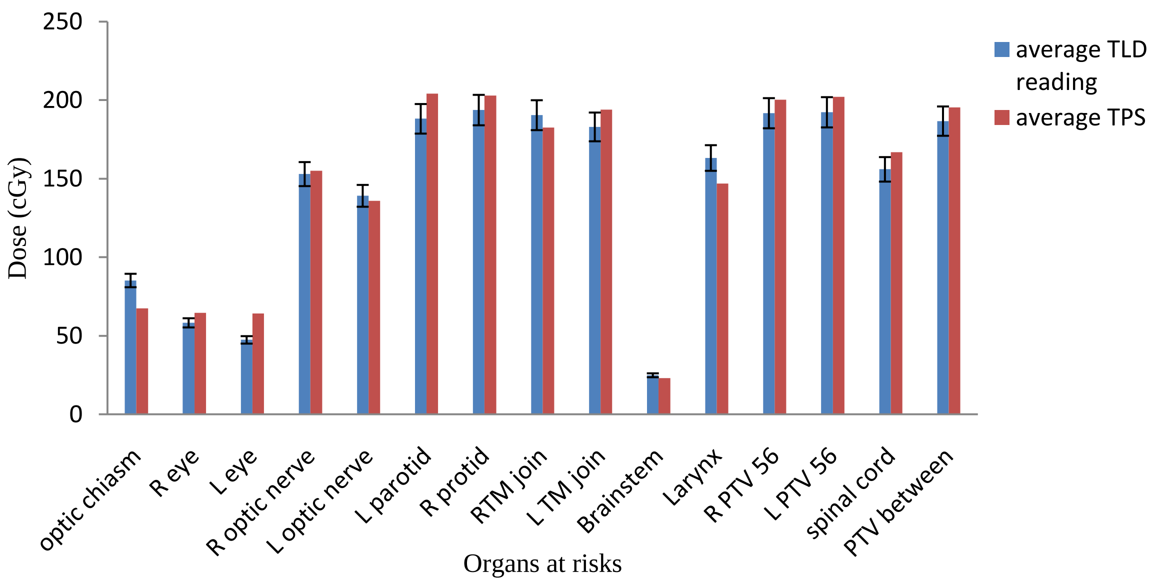


Fig. 6: Average TLD measurements (cGy) for three identical irradiation fractions compared to TPS predicted doses.



Abbreviations: TLD = Thermoluminecent Dosimeter; TPS=Calculated doses using treatment planning system; R=right; L=Left; TM Joint= Temporo-Mandibular Joint; PTV=Planning target volume

Fig. 7: Average of predicted doses at organs at risk (OAR) for three radiation sessions compared to average doses predicted by Treatment Planning System (TPS)

CONCLUSION

This is a new handmade design of anthropomorphic head and neck phantom intended for dosimetric verification of 3D-CRT plans. It was designed with movable slabs with delineated clinical organs that enable prediction of delivered doses at any organ of interest. The phantom's preliminary results have proved to be a valuable tool for 3D-CRT treatment dose verification. Implementation of this phantom in clinical head and neck 3D-CRT patient's plan verification would be considered in future work. Further modifications as finishing and holding technique are also will be considered.

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REFERENCES

Attix, F. H., (1986), *Introduction To Radiological Physics And Radiation Dosimetry*, First Ed. Wiley-VCH.

Brizel, D.M., Light, K., Zhou, S.M. and Marks, L.B., (1999), Conformal radiation therapy treatment planning reduces the dose to the optic structures for patients with tumors of the paranasal sinuses. *Radiother.Oncol.* 51: 215-218.

Cameron, J.R., Suntharalingam, N. and Kenney, G.N. (1968), *Thermoluminescent Dosimetry*. Univ. of Wisconsin Press.

Chung, H., Jin, H., Dempsey, J.F., Liu, C., Palta, J., Suh, T.S. and Kim, S., (2005). Evaluation of surface and build-up region dose for intensity-modulated radiation therapy in head and neck cancer. *Med. phys.* 32: 2682.

Ezzell, G.A., Galvin, J.M., Low, D., Palta, J.R., Rosen, I., Sharpe, M.B., Xia, P., Xiao, Y., Xing, L. and Yu, C.X., (2003), Guidance document on delivery, treatment planning, and clinical implementation of IMRT: *Report of the IMRT subcommittee of the AAPM radiation therapy committee. Med.phys.* 30: 2089.

Furetta, C. and Weng, P.S., (1998), *Operational Thermoluminescence Dosimetry*: World Scientific Pub Co Inc.

Galvin, J.M., Ezzell, G., Eisbrauch, A., Yu, C., Butler, B., Xiao, Y., Rosen, I., Rosenman, J., Sharpe, M. and Xing, L., (2004), Implementing IMRT in clinical practice: a joint document of the American Society for Therapeutic Radiology and Oncology and the American Association of Physicists in Medicine. *Int.J.Radiat.Oncol.Biol.Phys.* 58: 1616.

Gillis, S., De Wagter, C., Bohsung, J., Perrin, B., Williams, P. and Mijnheer, B.J., (2005), An inter-centre quality assurance network for IMRT verification: results of the ESTRO QUASIMODO project. *Radiother.oncol.* 76:340-353.

Horowitz, Y.S., (1984), *Thermoluminescence and Thermoluminescent Dosimetr*y, First Ed, CRC Press

Ibbott, G.S., Molineu, A. and Followill, D.S., (2006), Independent evaluations of IMRT through the use of an anthropomorphic phantom. *Techn.cancer.res.treat*. 5: 481.

ICRU (International Commission On Radiation Units And Measurements), (1989), Tissue Substitutes in Radiation Dosimetry and Measurement. Rep. 44, ICRU, Bethesda, MD

Kinhikar, R., Upreti, R., Sharma, S., Tambe, C. and Deshpande, D., (2007), Intensity modulated radiotherapy dosimetry with ion chambers, TLD, MOSFET and EDR2 film. *Australas.Phys Eng.Sci.Med*. 30: 25-32.

Kron, T., (1999), Applications of thermoluminescence dosimetry in medicine. *Radiat.protec. dosi.* 85: 333.

Leal, M.A., Viegas, C., Viamonte, A., Campos, A., Braz, D. and Clivland, P., (2010), Thermoluminescent chip detector for in vivo dosimetry in pelvis and head & neck cancer treatment. *Appl.Radiat.Iso*. 68: 795-798.

Lee, J., Yeh, C., Hsu, S., Shi, M., Chen, W. and Wang, C., (2008), Simple dose verification system for radiotherapy radiation. *Radiat.Measur.* 43: 954-958.

Lohr, F., Pirzkall, A., Debus, J., Rhein, B., Hass, A., Schlegel, W. and Wannenmacher, M., (2000), Conformal three-dimensional photon radiotherapy for paranasal sinus tumors. *Radiother.Oncol.* 56: 227-231.

Mayles, W., Heisig, S. and Mayles, H., (2000), Treatment verification and in vivo dosimetry. *Radiother.Phys.* 227-251.

McKeever, S.W.S., Moscovitch, M. and Townsend, P.D., (1995), *Thermoluminescence Dosimetry Materials: Properties And Uses*: Nuclear Technology Publishing.

Molineu, A., Followill, D. S., Balter, P. A., Hanson, W.F., Gillin, M.T., Huq, M.S, Eisbruch, A. and Ibbott, G.S., (2005). Design and implementation of an anthropomorphic quality assurance phantom for intensity-modulated radiation therapy for the Radiation Therapy Oncology Group. *Int.J.Radiat.Oncol.Biol.Phys.* 63: 577-583.

Pommier, P., Ginestet, C., Sunyach, M.P., Zrounba, P., Poupart, M., Ceruse, P., Ciupea, C., Carrie, C. and Montbarbon, X., (2000), Conformal radiotherapy for paranasal sinus and nasal cavity tumors: three-dimensional treatment planning and preliminary results in 40 patients1. *Int.J.Radiat.Oncol.Biol.Phys.* 48: 485-493.

Radaideh, K. and Alzoubi. A. (2010), Factors impacting the dose at maximum depth dose (dmax) for 6 MV high-energy photon beams using different dosimetric detectors. *Bioheal.Sc. Bull*. 2: 38-42.

Rasch, C., Eisbruch, A., Remeijer, P., Bos, L., Hoogeman, M., van Herk, M. and Lebesque, J. V., (2002), Irradiation of paranasal sinus tumors, a delineation and dose comparison study. *Int.J.Radiat.Oncol.Biol.Phys***.** 52: 120-127.

Roa, W. H. Y., Hazuka, M. B., Sandler, H. M., Martel, M. K., Thornton, A. F., Turrisi, A. T., Urba, S., Wolf, G.T. and Lichter A.S., (1994). Results of primary and adjuvant CT-based 3-dimensional radiotherapy for malignant tumors of the paranasal sinuses. *Int.J.Radiat.Oncol.Biol.Phys***.** 28: 857-865.

Rudén, B.I., (1976), Evaluation of the clinical use of TLD. Acta radiol. 15: 447.

Santvoort, J. P. C. and Heijmen, B., (1996), Dynamic multileaf collimation withouttongue-and-groove'underdosage effects. *Physics in Medicine and Biolog*y. 41: 2091.

Tsuji, H., Kamada, T., Arimoto, T., Mizoe, J.E., Shirato, H., Matsuoka, Y. and Irie, G., (1986), The role of radiotherapy in the management of maxillary sinus carcinoma. *Cancer***.** 57: 2261-2266.

Van Dam, J. and Marinello, G., (1994). Methods For In Vivo Dosimetry In External Radiotherapy: Garant.

Van Esch, A., Bohsung, J., Sorvari, P., Tenhunen, M., Paiusco, M., Iori, M., Engström, P., Nyström, H. and Huyskens D.P., (2002), Acceptance tests and quality control (QC) procedures for the clinical implementation of intensity modulated radiotherapy (IMRT) using inverse planning and the sliding window technique: experience from five radiotherapy departments. *Radiother.oncol*. 65: 53-70.

Webster, G.J., (2008), Design and Implementation of a Head & Neck Phantom (HANK) for System Audit and Verification of IMRT. *J.Appl.Clin.Med.Phys*. 9.

Yazici, N. 2004. The influence of heating rate on the TL response of the main glow peaks 5 and 4+ 5 of sensitized TLD-100 treated by two different annealing protocols. *Nucl.Instrum.Methods.* 215: 174-180.